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France-Australia Technical Arrangement TA 1/99 – Work Package 2: Ab initio estimation of composite properties

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ABSTRACT

Substantial savings could be made in the cost of airworthiness certification of composite aircraft structure if material properties could be predicted solely on the basis of the properties of the constituent fibres and resin. The feasibility of this approach was tested by surveying the literature on the prediction of compression strength. The literature is extensive and indicates that the compression failure process is well understood. The critical factors controlling compression behaviour are the shear stiffness and strength of the composite, not just the resin alone, and misalignment between the load bearing fibres and the loading axis. Relations do exist that characterise the key failure features, including compression strength, however all of these models require some data that must be obtained by testing the composite. In particular the shear stress/shear strain behaviour of resins changes in the presence of fibres so this must be measured experimentally. Gross and local fibre orientation must also be measured. It was concluded that the prediction of compression strength on the basis of fibre and resin properties alone awaits substantial improvements in understanding of the effect of fibres on the shear behaviour of resins and techniques to quantify fibre misalignment.

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Executive Summary

The cost of certifying advanced fibre composite aircraft structure is very high, largely because substantial testing is required at the coupon, element, detail, component and full-scale level. Even the basic mechanical properties of composite materials must be established by test because, at present, they cannot be predicted analytically.

Compression strength is usually the critical mechanical property (design allowable) in composite aircraft structure. Thus airworthiness certification requires that significant effort be directed at determining the various compression properties – compression strength, open-hole compression strength, filled-hole compression strength and compression-after-impact strength. Unfortunately compression tests are expensive to perform because they require close tolerances and extensive data acquisition.

Ideally the compression strength of composites, and all other design allowables for that matter, would be calculated analytically through knowledge of the behaviour of the fibres and resin alone. The aim of the France/Australia Technical Arrangement (TA1/99) "New Certification Procedures for Composite Materials", Work Package 2, was to survey the literature and establish whether the compression strength of composites could be predicted on this basis. If successful this technique may be used in the short term to rapidly screen new materials and in the longer term to predict coupon properties. Both of these outcomes would lead to a reduced number of tests.

The literature was reviewed. It was concluded that there is a good understanding of the compression failure process and the key variables. Compression loads in continuous fibre composites are supported by those fibres that are parallel to the loading direction. At a critical load the resin fails in shear, allowing the load bearing fibres to buckle locally into a feature known as a microbuckle. Microbuckles tend to propagate unstably, causing immediate catastrophic failure of the composite. The critical variables in this process are the shear strength and stiffness of the composite (not the resin alone) and the misalignment angle between load bearing fibres and the direction of loading. Relations do exist that characterise the key failure features, including compression strength, however all of these models require some data that must be obtained by testing the composite. In particular the shear stress/shear strain behaviour of resins changes in the presence of fibres and this must be measured experimentally. The distribution of orientations in the load bearing fibres is also critical and must be measured for different fibres and fibre forms (such as unidirectional prepreg tape, plain weave prepreg fabric, plain weave dry fabric, etc.).

This paper represents the final report on the Australian component of France/Australia TA 1/99 Work Package 2. As with the equivalent French report, it finds that current models cannot predict compression strength of composites on the basis of just the properties of the fibres and resin alone. For this to occur substantial improvements are required in understanding the effect of fibres on the shear behaviour of resins and techniques to quantify fibre misalignment.

Contents

1. Introduction

The cost of certifying advanced fibre composite aircraft structure is very high, largely because substantial testing is required at the coupon, element, detail, component and full-scale level. Even the basic mechanical properties of composite materials must be established by test because it is not possible to predict their mechanical properties on the basis of the constituent properties alone.

The critical mechanical property in the design of composite aircraft structure is usually compression strength. Significant effort is therefore directed at determining the various compression properties – compression strength, open-hole compression strength, filled-hole compression strength and compression-after-impact strength. Unfortunately compression tests are quite difficult to perform experimentally. Load must be introduced uniformly over the cross-section of the specimen and specimens must be restrained to prevent Euler (gross) buckling. As a result there are very tight tolerances on specimen dimensions (particularly parallelism of specimen ends) and test fixture alignment, and a need for strain measurement beyond that for other coupon level tests. Even by complying with these requirements, there is still some conjecture regarding the applicability of some standard compression test methods. Clearly obtaining compression properties of composite materials is an expensive business.

Ideally the compression strength, and for that matter all other mechanical properties, of advanced fibre composites could be calculated analytically through knowledge of the behaviour of the fibres and neat resin. With this approach the behaviour of new fibre/matrix systems could be predicted and testing would only need to be performed to verify the predicted performance of down-selected material systems.

The aim of the work presented in this report was to review the existing models for predicting compression strength and to assess whether any of these models could be used to predict strength on the basis of the properties of the constituents alone.

2. Modelling

2.1 Background

A significant volume of literature is devoted to compression behaviour. Many hundreds of publications report the compression strength/modulus/failure strain of composite materials. The majority of these simply report the results of compression tests and are of no practical value in the development of a predictive model because the parameters that are required in such models are not reported. A few hundred or so of these publications attempt to analyse compressive behaviour and explain the reasons for the observed behaviour. This analysis ranges from a cursory examination of the properties and a superficial explanation of behaviour, through more detailed experimental observation and comprehensive explanations, to detailed numerical or theoretical modelling of fibres/resins/composites.

The most significant developments have arisen from the latter approach, theoretical modelling of composites with a minimum of simplifying assumptions and experimental validation to ensure that the model predictions match the observed behaviour. There have been three fundamental developments in the prediction of compression strength. The first was by Rosen [1] who modelled composites with purely elastic properties. These produced a gross overestimation of observed strengths. The major breakthrough came when Argon [2] recognised that compression strength was dictated by the buckling strength of the fibres in the resin, and was thus critically dependent on the angle of the load bearing fibres to the loading axis. Budiansky [3] added to this by recognising that fibre buckling was a localised phenomenon. Fibres failed in localised regions called kink bands or microbuckles, the generation of which was dependent on the shear strength of the matrix. Subsequent work has enhanced the body of knowledge regarding the nature of kink bands, and improved prediction of the properties of these bands, but it has not changed the fundamental understanding of the failure process.

Despite this understanding there is still no widely accepted model to predict the compression strength of composite laminates that uses just the basic properties of the fibre and resin.

2.2 Elastic beams in elastic foundation (Rosen)

The first major contribution to the modelling of fibre composite compression strength was given by Rosen [1]. His model was based on the hypothesis that individual fibres buckle in short wavelength patterns in a fashion analogous to buckling of a column or plate on an elastic foundation.

Rosen considered two theoretical modes of buckling. These were the extensional and shear modes as shown in Fig. 1. In the extensional mode, adjacent fibres buckle in opposite directions and the major deformation in the matrix between these fibres is in a direction perpendicular to the fibres. In the shear mode the fibres buckle with the same wavelength and in-phase. In this situation the matrix deforms primarily in shear.

The fibres were modelled as straight, perfectly aligned, plates separated by an elastic matrix. An energy method was used to calculate the buckling stress. The strain energy in the loaded composite with straight fibres was compared with that of a composite under the same load, but with fibres deformed in each of the buckled modes. The results for the extensional and shear mode are shown in Equations 1 and 2 respectively. In the range of fibre volume fractions typical of advanced fibre composites, 0.4 to 0.7, the strength of the shear mode was much lower than the extensional mode and therefore considered to be the dominant failure mechanism. Equation 2 is the classic Rosen equation for compression strength.

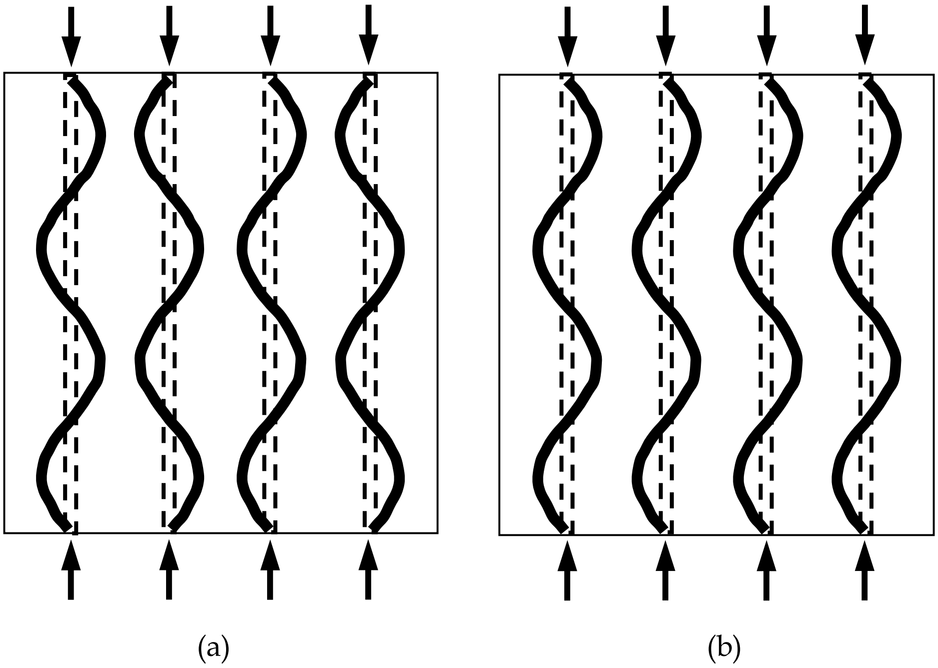


Figure 1: The (a) extensional and (b) shear modes defined by Rosen [1]

$$\sigma_c = 2V_f \sqrt{\frac{V_f E_m E_f}{3(1 - V_f)}} \tag{1}$$

$$\sigma_c = \frac{G_m}{1 - V_f} \tag{2}$$

Where:

- σ_c = compression strength
- V_f = fibre volume fraction
- E_m = elastic modulus of matrix
- E_f = elastic modulus of fibres
- G_m = shear modulus of matrix

The very high levels of compression strength predicted by Equation 2 prompted Rosen to consider the effects of plasticity in the matrix. He assumed that the moduli of the matrix, E_m and G_m, decreased from its elastic value at 1 % shear strain to zero at 5 % shear strain. This reduced the predicted strength and Rosen claimed that, although the inelastic compression strength had not been measured, they were not unreasonable.

The compression strength predicted using Equation 2, even corrected for the effects of plasticity, was still up to an order of magnitude larger than that observed in compression tests. A subsequent energy analysis derivation produced a relation similar to Equation 2, but the shear modulus was modified as shown in Equation 3 [4-7]. Equation 3 was an improvement over Equation 2 because, in addition to stiffness of the matrix, G_{LT} accounted for the fibre and fibre-matrix interface. However the predictions using this technique were still much higher than observed compression strengths.

$$\sigma_c = G_{LT} \tag{3}$$

Where:

G_{LT} = in-plane shear modulus of the composite

A further refinement of this approach was to account for matrix plasticity. It was found that G_{LT} is non-linear for boron/epoxy [8], decreasing as the applied axial load increases. In one work it was suggested that G_m from Equation 2 be replaced by the inelastic tangent shear modulus of the matrix [9]. Other workers found that a factor of 0.63 was required to reduce the tangent modulus so that it matched the compression strength [10]. Since there was no theoretical basis from which this factor was chosen, it was not considered practicable for use with other materials.

2.3 Misaligned fibres (Argon)

The most significant development in the prediction of compression strength was the recognition that strength is critically dependent on the alignment between the load bearing fibres and the loading axis. This insight has been attributed to Argon [2], who stated that the compression failure of a fibre composite occurred by a kinking process similar to kink band formation in metal crystals. This produces the in-phase buckling shown in Fig. 1 (b), but at a stress far below the ideal buckling strength predicted by Rosen.

Argon considered a region of fibres that were initially misaligned with the compression axis. The compressive stress induced a shear stress ($\tau = \sigma\, \phi_0$) at the interface between the fibre and the matrix. The fibre would slide relative to the matrix and rotate to further increase the resolved shear stress when the induced shear stress reached the interlaminar shear strength. This would produce a local instability that would propagate as a shear collapse band. The compression strength was therefore expressed by Equation 4.

$$\sigma_c = \frac{k}{\phi_0} \tag{4}$$

Where:

k = interlaminar shear strength of the composite

ϕ_0 = initial misalignment angle between the fibre and the compression axis

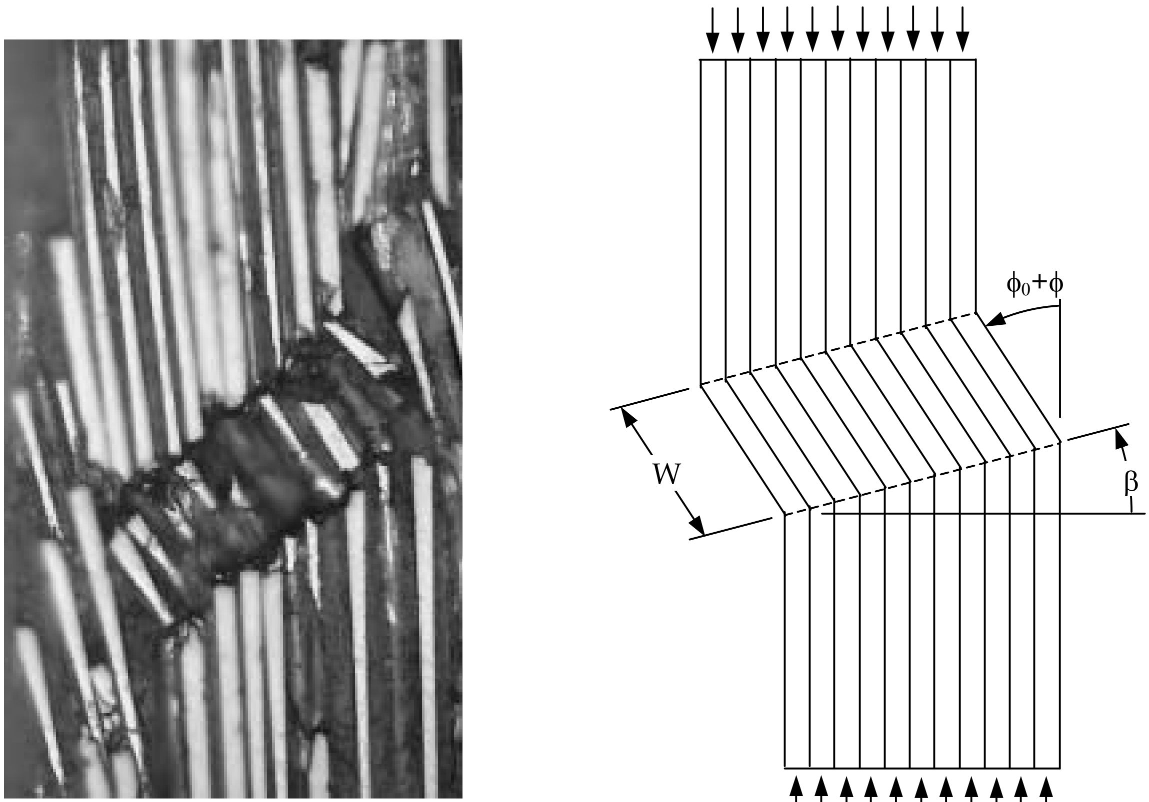
Although this simple relation represented a significant improvement in understanding of the compression failure, it suffered from two major deficiencies. The first was that it did not account for the effect of matrix plasticity. The second deficiency was in defining a meaningful measure of fibre misalignment. This is explored in more detail in Section 3.

2.4 Kink bands (Budiansky)

Budiansky [3] supported Argons argument that internal buckling of fibres is a likely mode of failure for composites subjected to compression loading. However the concept was extended to state that failure is localised into narrow bands, called kink bands or micrbuckles. The presence of microbuckles was first described by Berg and Salama [11] and in more detail by Evans and Adler [12]. The Budiansky description of the microbuckle, as shown in Fig. 2, is accepted as the characteristic feature of compression failure in fibre composites. The aim of most work subsequent to this has been to refine our understanding of this fundamental failure process.

The classical Budiansky plastic fibre microbuckling model is shown in Equation 5. It was noted that this relation degenerates to the Rosen result (Equation 3) for $\phi_0 = 0$ and the Argon result (Equation 3) if $\gamma_y << \phi_0$.

$$\sigma_c = \frac{\tau_y}{\phi_0 + \gamma_y} \tag{5}$$



(a) (b)

Figure 2: (a) Micrograph and (b) diagrammatic representation of a microbuckle [3]

Where:

τ_y = yield shear strength of the composite
γ_y = yield shear strain of the composite

This work also proposed that microbuckle width (W) could be predicted using Equation 6. This relation was derived by assuming that fibres undergo inextensional bending until they break while the matrix is rigid-plastic. For reasonable data this relation predicted $W/d \approx 12$, which was in good agreement with experimental observations of $W/d \approx 10$.

$$\frac{W}{d} = \frac{\pi}{4}\left(\frac{2\sqrt{\tau_y{}^2 + \sigma_{Ty}{}^2\tan^2\beta}}{V_f E}\right)^{-\frac{1}{3}} \tag{6}$$

Where:

W = microbuckle width
d = fibre diameter
σ_{Ty} = transverse stress at yield
β = microbuckle angle
V_f = fibre volume fraction
E = fibre modulus

Budiansky recognised that microbuckles were inclined ($\beta \neq 0$). Experimental observations showed that $\beta \approx 10$ - $30°$, however his model predicted $\beta = 0$. Theoretical treatment of inclined microbuckles by Budiansky was commenced in reference [3] and continued in reference [13]. Kyriakides [14] used finite element modelling to analyse the failure process. These models could predict, with reasonable accuracy, the inclination of microbuckles.

2.5 Key factors

It appears that the key factors governing compression have been identified. These are the shear strength and stiffness of the composite (matrix in the presence of fibres) and fibre misalignment. To improve compression strength it is necessary to increase shear stiffness and strength, and eliminate fibre misalignment. Section 2 discusses some of the observations that have been made with regard to fibre waviness.

3. Fibre misalignment

3.1 Misalignment in actual composites

All fibres exhibit some misalignment with the nominal ply direction, both as a gross misalignment from one end to the other and as shorter perturbations along their length. Gross misalignment is the difference between the nominal and actual ply direction and is created during the lay-up process. It is virtually impossible to eliminate in the manual lay-up of pre-pregs, particularly over complex profiles. It is possible that these differences may be even worse in liquid moulding processes such as resin transfer moulding because the lay-up is made of dry fabric plies. Unless special precautions are taken to prevent the relative movement of plies in the mould, it is possible that these may move during mould closure or resin infusion. In contrast, the robots and narrow tape widths used in automatic tape laying decrease substantially any gross fibre misalignment.

Shorter perturbations are caused by the fibre forming process and accidental inclusion of debris during lay-up. The fibre forming does not refer to whether the fibres are PAN or pitch based, but rather how they are brought together in the tape/fabric/preform. Figure 3 shows the alignment of fibres in a plate of cured prepreg tape [14]. It was claimed that this regular pattern of fibre imperfections was caused by the method used to lay the fibres in the prepreg tape. The type and extent of perturbations will vary depending on the forming process. For example woven fabrics will have regular, and possibly quite substantial, undulations where the fibre tows crossover. In addition these tows will be damaged (frayed) by abrasion with weaving loom machinery during the weaving process and by contact with intersecting fibre tows.

3.2 Experimental measurement of fibre misalignment

The measurement of fibre misalignment is based on analysis of micrographs of polished cross-sections. In the most widely cited of these [15], specimens were sectioned at an acute angle relative to the load-bearing ply. The cross-section of load bearing fibres were ellipses, with the ratio of the minor to major ellipse length being proportional to the angle

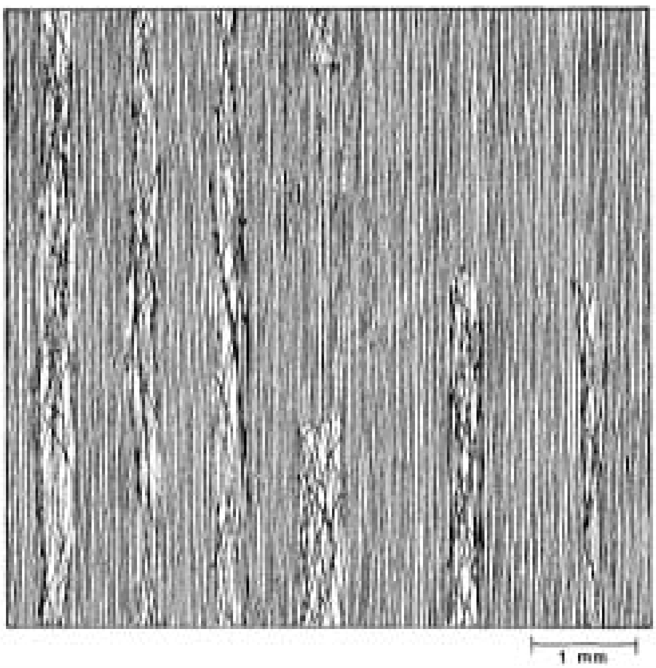


Figure 3: Schematic representation of fibre angles within a section of a prepreg [14]

between the surface of the polished section and the fibre. An estimation of the distribution of fibre angles was obtained by measuring the axes lengths of a large number of fibres.

The major deficiency with this technique is that each specimen provides data for only one location through the laminate. Specimen sectioning, mounting, polishing, photography and analysis is a time consuming and labour intensive process, even with automated polishing and image analysis equipment. To gain an accurate understanding of the distribution of fibre orientations along the length and across the width of a composite component would require the preparation and analysis of a number of specimens.

Despite the significant effort required with the sectioning technique, it appears that it is the only practicable approach at present. No literature has been identified that details alternative techniques. Ideally such an alternative would be non-destructive and interrogate statistically representative volumes of material but not produce excessive volumes of data. Measuring the spatial coordinates of a statistically significant number of fibres is not considered viable because the data files would be massive.

Fortunately it is the fibre misalignment angles and not the fibre coordinates that are important. It is conjected that gross fibre orientation and local misalignment may be measured with a diffraction technique such as X-ray diffraction (XRD). When metals or ceramics are imaged with XRD, planes of atoms appear as spots. The location of these spots can be related to the orientation of atomic planes while the spreading/distortion of spots can be related to residual stress. A similar process may be used to measure fibre misalignment. For example the diffraction pattern of a ply may be a diffuse spot, with the centre of the spot representing the gross ply orientation and the characteristics of the spot (size of diffuse zone) represent misalignment about that gross orientation. A major technical problem for this approach is to identify radiation of the appropriate wavelength to be diffracted by fibres (the wavelength of infrared radiation is comparable to that of 7-8 μm diameter carbon fibres), and with sufficient energy to penetrate through consolidated laminates (10 MeV X-rays can penetrate 2 cm into composites [16] but their wavelength is 10^{-8} μm, eight orders of magnitude too short to diffract around fibres). Substantial research would be required to evaluate the feasibility of such an approach.

3.3 ϕ as a measure of misalignment

A major problem is how to characterise fibre alignment and perturbations. The most common approach is to select a single value of ϕ_0 that correlates predictions from a model with experimental data. The values of ϕ_0 obtained by this approach appear reasonable, with $\phi_0 \approx 2$-3° being typical for Equation 5 to predict compression strengths that match experimental observations. However microscopy of actual composites has shown that the average misalignment can be much better, typically $\phi_0 \approx 1°$.

Barbero and Tomblin [17] indicated that using the average misalignment is a meaningless measure because the nominally load bearing fibres will all be clustered around 0°. Since misalignment occurs in both the $+\phi_0$ and $-\phi_0$ directions, a simple arithmetic average angle does not adequately represent the effect of these misalignments. As an alternative some workers have measured the distribution of misalignment angles in a section of the composite and used the standard deviation of this distribution as the measure of misalignment [14, 18]. This approach is flawed too because standard deviation is a measure of the dispersion of a distribution, not a representative misalignment.

Barbero [19] derived Equation 7 as an explicit relation for the prediction of compression strength of a unidirectional composite using an imperfection sensitivity approach with a continuum damage model. The key considerations in this work were that the fibre misalignment was a Gaussian distribution and the shear stress/shear strain relation must be non-linear and that for the composite (not the neat resin). It was claimed that the advantage of this approach over previous work was that the variables, G_{LT}, τ_y and Ω, could be measured by experiment and did not require any "factoring" to correlate the predictions with experimental data.

$$\frac{\sigma_c}{G_{LT}} = \left(\frac{G_{LT}\Omega}{a\tau_u} + 1 \right)^b \tag{7}$$

Where:

Ω	=	standard deviation of misalignment angle
τ_u	=	shear strength of the composite
a	=	0.21
b	=	-0.69

and:

$$3500 < G_{LT} < 8000 \text{ MPa}$$
$$40 < \tau_y < 160 \text{ MPa}$$
$$\pi/180 < \Omega < 3.5\pi/180 \text{ radians}$$

4. Effect of notches

4.1 Introduction

Holes are an essential feature of aircraft structures such as skins, control surfaces, ribs, spars, stringers, doors and fairings. Open-Hole-Compression (OHC) coupons were tested as part of TA1/99 Work Package 1 [20].

It is well known that the tensile and compression strength of composite laminates falls disproportionately with hole diameter. As shown in Fig. 4, this fall is larger than that predicted by simple net section stress, but not as large as that predicted by the stress concentration factor for brittle failure. For this reason open-hole-tension and OHC

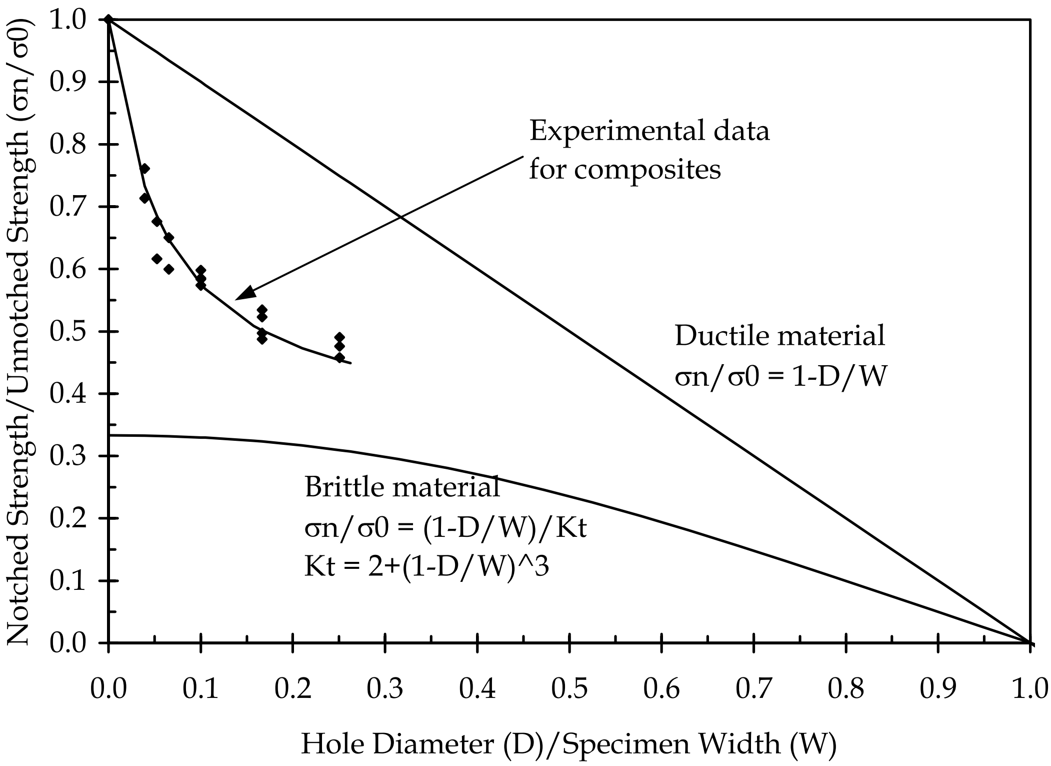


Figure 4: Plot showing that the tensile strength of a notched composite is less than that predicted for a ductile material but greater than that predicted for a purely brittle material

strengths are usually measured experimentally. They form part of the coupon level of testing in airworthiness certification test programs.

A variety of models have been developed to predict the effect of holes on strength in an effort to reduce reliance on experimental test data. One class of model incorporates a length scale. Failure is predicted to occur when the stress or strain at some characteristic distance (the so called length scale) ahead of the hole reaches a critical value. These models are used widely because they are capable of predicting failure under uniaxial loading conditions with sufficient accuracy for aircraft design. Three such models are reviewed in the remainder of Section 4.

4.2 Point and average stress criterion (Whitney and Nuismer)

Whitney and Nuismer [21] developed two criteria to account for the effect of holes on the tensile strength of composite laminates. They are commonly referred to as the average stress criterion and the point stress criterion. Both were developed to model the situation shown in Fig. 4 where the loss in strength was observed to be greater than that due to the reduction in net section but less than that due to a classical stress concentration factor (SCF).

4.2.1 Average stress criterion

The average stress criterion hypothesises that failure occurs when the average normal stress, at a characteristic distance ahead of the hole (a_0), reaches the unnotched strength of the laminate (σ_0). This criterion can be expressed diagrammatically as in Fig. 5 (a) or mathematically by Equation 8. An explicit expression for the notched strength of an infinite isotropic plate containing a circular hole with a uniform remote stress is shown as Equation 9.

$$\sigma_0 = \frac{1}{a_0}\int_{x=r}^{x=r+a_0} \sigma_y(x,0)dx \tag{8}$$

Where:

a_0 = characteristic distance
σ_0 = unnotched strength
$\sigma_y(x,0)$ = the normal stress along the ligament from the hole in the direction transverse to the loading axis (x axis in Fig. 5)

$$\frac{\sigma_N}{\sigma_0} = \frac{2(1-\xi_1)}{2-\xi_1^{\ 2}-\xi_1^{\ 4}+(K_T^\infty-3)(\xi_1^{\ 6}-\xi_1^{\ 8})} \tag{9}$$

Where:

ξ_1 = $\frac{r}{r+a_0}$
σ_N = notched strength
r = hole radius
K_T = stress concentration factor

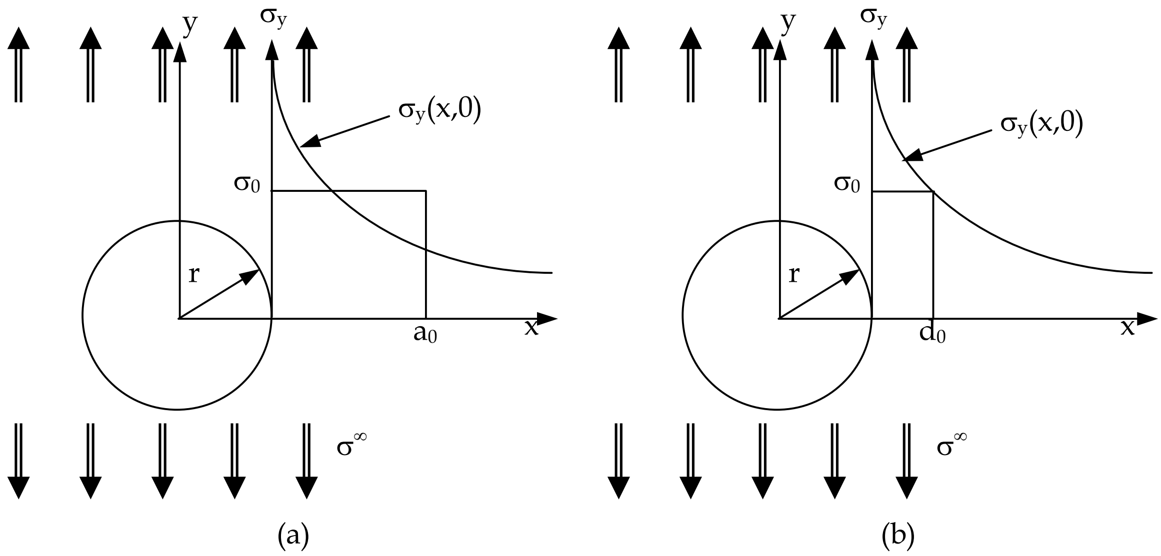


Figure 5: (a) Average and (b) point stress failure criteria for a circular though thickness hole in an infinite plate [21]

Two material parameters, σ_o and a_o, are required to predict notched strength using this model. The unnotched strength is typically determined from tests on the subject laminate, although it may be determined through laminate plate theory and the application of unidirectional material allowables, however the accuracy of any results from this approach must be treated with caution. The characteristic distance is determined by curve fitting with strength data from tests at two or more hole sizes.

4.2.2 Point stress criterion

As implied in Fig. 5 (b), the point stress criterion assumes that failure occurs when the stress at some characteristic distance (d_0) ahead of the discontinuity is equal to the strength of the unnotched material (σ_0). The failure criterion, expressed as the ratio of notched to unnotched strength for an isotropic lay-up, is shown in Equation 10. For this model d_0 is established by curve fitting strength data for specimens with no hole (σ_0) and at least one hole size.

$$\frac{\sigma_N}{\sigma_0} = \frac{2}{2 + \xi_2{}^2 + 3\xi_2{}^4} \tag{10}$$

Where:

$\xi_2 \quad = \quad \dfrac{r}{r + d_0}$

$d_0 \quad =$ characteristic distance

Both Equations 9 and 10 reduce to the SCF criterion, that is $\sigma_N/\sigma_0 = 1/3$, for large values of r and to $\sigma_N/\sigma_0 = 1$ for small values of r.

4.3 Cohesive zone model (Soutis)

The cohesive zone model applies only to specimens loaded in compression. It assumes that compression loads are supported exclusively by the 0° plies (those plies parallel to the loading axis) and that failure in these plies occurs by microbuckling. The microbuckle initiates at the edge of the hole and, initially, propagates stably. Upon reaching a critical length the microbuckle propagates unstably, thereby producing catastrophic failure of the ply. This simultaneously causes specimen failure. Experimental evidence supports this model of compression failure in the presence of holes [22].

The following explanation of the model is taken from reference [22]. Microbuckle initiation is assumed to occur when the stress at the edge of the hole reaches the unnotched strength of the laminate. The damage process zone, including the microbuckle, delamination, matrix cracking, plastic deformation and damage in off-axis plies, is represented as an equivalent line crack. This equivalent crack is loaded on its faces by a normal bridging traction that decreases linearly with the closing displacement of the crack. When the load on the specimen is increased the equivalent crack grows in length, representing microbuckle growth. The length of this equivalent crack is predicted by requiring that the total stress intensity factor (sum of stress intensity factor due to the remote stress and stress intensity factor due to local bridging traction) equal zero. The equivalent crack length is solved as a function of the remote stress by matching the crack opening profiles from the bridging law with that deduced from the elastic solution for a cracked body. The crack length is plotted as a function of applied stress. There is a maximum that corresponds to the compression strength. The crack length at this stress is the critical length of equivalent crack. This may be visualised as the length of microbuckle required to initiate catastrophic failure of the laminate.

Two parameters are required for this model, the unnotched compression strength and the fracture toughness, as expressed by the critical stress intensity factor K_c, of the laminate. This fracture toughness is that of the laminate loaded in-plane, with a through thickness crack propagating perpendicular to the loading direction. It is measured using centre notch coupons loaded in compression. Values of 35-50 MPa √m were measured for a range of T800/924C laminates [22] although it was stated that typical values for carbon fibre composites are 40-50 MPa √m.

The cohesive zone model has been implemented in the Composite Compressive Strength Modeller (CCSM) software package distributed by Cambridge University [23]. The CCSM firstly requires the elastic properties of the unidirectional lamina. It uses laminate theory to combine these into the elastic properties of the laminate. The type of loading, specimen geometry and critical stress intensity factor are the remaining inputs.

5. Conclusion

Compression strength is often the critical material property in the design of composite aircraft structure. There is a substantial body of literature focused on predicting compression behaviour. The critical factors controlling compression strength are the shear stiffness and strength of the composite and misalignment between the load bearing fibres and the loading axis. A variety of analytical and numerical formulations are available to predict strength, however all require at least one (and often more) measurement to be made on the composite. It is concluded that the prediction of compression strength on the basis of fibre and resin properties alone awaits substantial improvements in understanding of the effect of fibres on the shear behaviour of resins and techniques to quantify fibre misalignment.

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19. ABSTRACT

Substantial savings could be made in the cost of airworthiness certification of composite aircraft structure if material properties could be predicted solely on the basis of the properties of the constituent fibres and resin. The feasibility of this approach was tested by surveying the literature on the prediction of compression strength. The literature is extensive and indicates that the compression failure process is well understood. The critical factors controlling compression behaviour are the shear stiffness and strength of the composite, not just the resin alone, and misalignment between the load bearing fibres and the loading axis. Relations do exist that characterise the key failure features, including compression strength, however all of these models require some data that must be obtained by testing the composite. In particular the shear stress/shear strain behaviour of resins changes in the presence of fibres so this must be measured experimentally. Gross and local fibre orientation must also be measured. It was concluded that the prediction of compression strength on the basis of fibre and resin properties alone awaits substantial improvements in understanding of the effect of fibres on the shear behaviour of resins and techniques to quantify fibre misalignment.